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DETECTION OF LOCALIZED HEAT DAMAGE IN A POLYMER MATRIX COMPOSITE BY THERMO-ELASTIC METHOD (PREPRINT)

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14. ABSTRACT
Reduction of strength of polymer matrix composites when exposed to high temperatures is a major concern in aerospace industry. Loss of mechanical strength can be measured only through established destructive techniques; there is a need for detection and evaluation of heat damage in PMC. This paper describes a thermo-elastic based non-contact nondestructive technique for detection and evaluation of heat damage in PMC. The efficiency of the material to convert acoustic energy into heat is used as a means to detect and evaluate the heat damage in the material. A panel subjected to local heat damage at several locations is tested using air coupled ultrasonic C-scan and thermo-elastic measurements. The results show that the ultrasonic C-scan detects only the major damage. On the other hand the thermo-elastic method detects both high and low level heat damages in the panel. The efficiency of the conversion of acoustic energy into heat, in undamaged and damaged regions and its role in detecting damage are discussed.

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DETECTION OF LOCALIZED HEAT DAMAGE IN A POLYMER MATRIX COMPOSITE BY THERMO-ELASTIC METHOD

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ABSTRACT

Reduction of strength of polymer matrix composites when exposed to high temperatures is a major concern in aerospace industry. Loss of mechanical strength can be measured only through established destructive techniques; there is a need for detection and evaluation of heat damage in PMC. This paper describes a thermo-elastic based non-contact nondestructive technique for detection and evaluation of heat damage in PMC. The efficiency of the material to convert acoustic energy into heat is used as a means to detect and evaluate the heat damage in the material. A panel subjected to local heat damage at several locations is tested using air coupled ultrasonic C-scan and thermo-elastic measurements. The results show that the ultrasonic C-scan detects only the major damage. On the other hand the thermo-elastic method detects both high and low level heat damages in the panel. The efficiency of the conversion of acoustic energy into heat, in undamaged and damaged regions and its role in detecting damage are discussed.

INTRODUCTION

Polymer matrix composites (PMCs) with high specific strength are important structural materials for aerospace applications. Recently there has been an increase in the use of PMC's in both civilian as well as military aircraft, which take advantage of both the high strength and light weight properties. The mechanical strength of PMCs can be dramatically reduced when these materials are exposed to temperatures approaching and beyond the glass transition temperature of the polymer matrix. This could occur as a result of an onboard fire, lightning strikes, runaway heating blankets (used in repair of composites on aircraft), exhaust impingement from missiles or engines and similar exposures [2]. Extensive heat damage causes charring, blistering, fiber-matrix debonds and delaminations, readily detectable through visual observation, and the majority of traditional NDE techniques. Nevertheless, laboratory studies have established that the PMC's can lose 10% to 80% of their mechanical strength when exposed to aggressive environments with no perceivable visible damage, detectable debonds, or delaminations [3]. This type of heat damage is often referred to as "incipient" heat damage. Detection and quantification of incipient heat damage is of significant concern in PMC aerospace structures.

According to recent reviews [4, 5], most of the NDE techniques based on ultrasound, electromagnetics, and thermography that are able to detect major surface and sub-surface heat damage are not sensitive enough to detect incipient heat damage. Conversely, spectroscopic based techniques such as laser induced fluorescence (LIF) have shown significant promise in detecting not only major damage but incipient damage in PMCs [6, 7]. Recent investigations indicate that the technique can be used over large areas. However, its optical nature limits its sensitivity to surface damage. Therefore, the LIF

technique cannot be used nondestructively for detection and evaluation of bulk damage that might occur in the interior of the material or the backside of the PMC. Thus, there is a need for development of NDE techniques that are capable of measuring damage thru-the-thickness of PMC's as well as to obtain a robust relation between the loss of mechanical strength and heat exposure in composite materials.

To overcome these limitations Sathish, et al [9] have proposed a thermo-elastic based method for qualitative and quantitative evaluation of heat damage in PMCs. Preliminary measurements indicate that the technique has potential to detect as well as provide a quantitative estimation of the heat damage in PMC's. This paper presents a detailed examination of the thermo-elastic measurements in heat damaged polymer composites. Local measurements on samples exposed to different times and temperatures are compared to investigate the possibility of developing in the future a quantitative method based on this technique to evaluate heat damage by determining a correlation to mechanical strength. Thermo-elastic measurements are compared with air-coupled ultrasonic images obtained on the same samples.

MATERIAL

An epoxy-carbon fiber composite panel consisting of a Hexcel 8552 resin matrix with Hexcel IM7 carbon fibers was used in the experiments. The dimensions of the sample are 260 mm (L) x 180 mm (W) x 2 mm (T), consisting of 16 layers with a $[0/+45/-45/90]_{2s}$ lay up. To replicate aircraft composite structure the panel had a fine copper mesh under a layer of paint applied to one side. The composite panel was heat damaged using a quartz lamp placed at a distance of 47 mm from the unpainted side of the sample. The lamp was focused to produce a spot 15 mm in diameter. The temperature during exposure was

monitored on the back side of the panel by placing one thermocouple (TC1) at the center, and another (TC2) offset 30 mm away from center. The panel was exposed to local heating at six different locations. While the duration of exposure at each location was varied the power to the quartz lamp was held constant. The locations, maximum temperatures as recorded by TC1 and TC2, and duration of exposure for all locations, HS1 to HS6, are shown in Table 1. Relative to pre-determined exposure times, HS1 and HS4 are defined as short exposures, HS2 and HS5 are intermediate exposures and HS3 and HS6 are long exposure. Figure 1 and Figure 2 are optical images of the heat exposed, unpainted side and the unexposed, painted side of the damaged panel. These figures illustrate that all locally heated zones show some degree of discoloration. At locations exposed to the longer durations some amount of surface bulging most likely due to surface ply delaminations occurred. In addition a loss of matrix material was observed with the longer exposure times.

EXPERIMENTAL TECHNIQUE

The approach of the non-contact thermo-elastic measurement technique is to excite the sample with a high amplitude acoustic device in a non-contact mode while the temperature change and out-of-plane displacements of the sample due to interaction of acoustic energy with the sample are measured. The instrumentation used to perform non-contact thermo-elastic measurement is shown in Figure 3. High amplitude acoustic waves are generated using an acoustic horn system consisting of a stack of piezo-electric transducers excited by a 20 kHz continuous wave RF signal. The mechanical waves at the end of transducer are passed to a booster to mechanically amplify the signal. The amplified acoustic signal is passed from the booster to a horn that further mechanically amplifies the signal to generate displacements on the order of 100 microns. The sample to be examined is placed in front

of the acoustic horn with at a predetermined distance creating an air gap. The horn standoff distance used in this study was determined by a systematic study to ensure that when the acoustic horn is excited it does not contact the sample. The IR camera is placed directly across from the center of the acoustic horn, and the sample is placed in between the acoustic horn and the IR camera. The IR camera is focused on the region that is directly opposite of the acoustic horn. Subsequent to the temperature measurements the IR camera is replaced by a fiber optic displacement sensor to capture the out of plane displacements. The fiber optic displacement sensor is carefully positioned in the same location that was being measured with the IR camera.

The thermo-elastic measurements are performed in two separate steps. First, the change in the temperature of the sample as a function of a series of electrical signals input into the piezo-stack and the acoustic horn is measured. Second, the acoustic displacement amplitude in the sample is measured as a function of the same electrical signals input to the piezo-stack and acoustic horn for the temperature measurement. To measure the change in temperature the experimental arrangement shown in Figure 3 is used. An electrical input to the ultrasonic horn system produces high amplitude acoustic waves. The acoustic waves propagate through the air gap and interact with the sample. The interaction produces a tiny amount of heat and a slight increase in temperature at the interaction region. The temperature increase is captured and measured using an IR camera.

In the second part of the experiment, a non-contact fiber optic displacement sensor is placed to measure the out of plane displacements of the sample directly across from the center of the acoustic horn. At the same electrical signal input levels used in the previous step the acoustic displacement amplitudes through the sample are recorded. Both the

temperature data and the displacement data are functions of the same series of electrical input. Therefore, two sets of experimental data can be reduced to a plot of the change in temperature as a function of acoustic displacement amplitude through the sample.

RESULTS AND DISCUSSION

The sample was subjected to an ultrasonic evaluation before and after heat exposure for comparing and baselining the thermo-elastic measurements. To avoid water infiltration into some of the delaminated locations a 25 mm diameter air coupled ultrasonic transducer operating at 1.1 MHz was scanned across the surface of the sample in pulse-echo mode. The large acoustic impedance difference between the sample and the air allows very little acoustic energy to propagate through the sample. Under these conditions it was not possible to observe a reflected signal from the back surface. As a result, instead of thru-the thickness scanning, scans were performed on the exposed, unpainted and back, painted side of the panel. Figure 4 and Figure 5 show the results of the ultrasonic scan for exposed and back side of the sample respectively. In Figure 4, damage locations of HS2, HS3, HS5 and HS6 on the exposed surface can be visually identified. However, Figure 5 shows that only HS3 and HS5 on the unexposed surface can be identified clearly while HS2 and HS6 are barely visible. Damage locations HS1 and HS4 are not visible in either image. The differences in contrast in the image are due to a combination of surface topography and acoustic impedance changes. The contrast indicates that at locations HS2, HS3, HS5 and HS-6 significant changes have occurred. At locations HS1 and HS4 there are no indications (delaminations, etc.) of any heat damage based on the ultrasonic scans. This is possibly due to the minimal changes in surface topography and acoustic properties of the material. While locations HS1 and HS4 cannot be defined as incipient damage since they

exhibit visible charring on the heat exposed surface. They are suitable for demonstrating the ability to detect heat damage through-the-thickness that does not induce delaminations.

Thermo-elastic measurements at locations HS4, HS5 and HS6 were performed by placing the acoustic horn close to the center of the damaged region. Temperature changes and the acoustic displacement through the thickness of the sample at each location were measured five times with averages of the temperature increase and the acoustic displacements recorded. Measurements were performed on an undamaged region as well as on the heat damaged locations HS4, HS5 and HS6. Figure 6 illustrates the average increase in temperature plotted as a function of average acoustic displacement taken through the thickness of the sample. The acoustic horn used in the present experiment produces a minimum of 0.7μm of displacement at the lowest possible amplitude settings. Thus the data was acquired between 0.7 μm and 1.7 μm. It is apparent from Figure 6, that the average temperature rise and displacement are dependent on the severity of damage. In particular, the average temperature rise decreases with increasing heat exposure time as the displacement increases. The experimental measurements were fit to a second degree polynomial and the coefficients were examined. Table 2 lists the coefficient of the second order term for all exposure times. In addition, the percent difference between damaged and undamaged states was calculated. It is observed that the percent difference increases with increasing time of exposure.

The fundamental mechanisms for producing variation in average increase in temperature due to heat damage are a complex mixture of thermal, elastic and visco-elastic properties of the composite material. During heat exposure all of the above properties are affected to a certain extent. Although an individual property may not change dramatically, there is a

possibility that the combination of properties might produce a significant observable change. The measurements described here detect and measure the conversion of acoustic energy by the material into heat. It is observed that the efficiency of the composite material to convert acoustic energy to heat decreases with the increasing heat damage.

CONCLUSIONS

A non-contact, thermo-elastic technique capable of detecting locations of heat damage in polymer matrix composites has been developed. The thermo-elastic response as a function of acoustic input amplitude decreases with increasing heat damage in the material. The relationship between thermo-elastic response and input acoustic amplitude has the potential to be used not only as an indicator of heat damage, but also a means to quantitatively correlate with mechanical strength degradation. Experimental measurements show that the non-contact, thermo-elastic technique was able to identify heat damage that ultrasonic C-scan imaging failed to identify.

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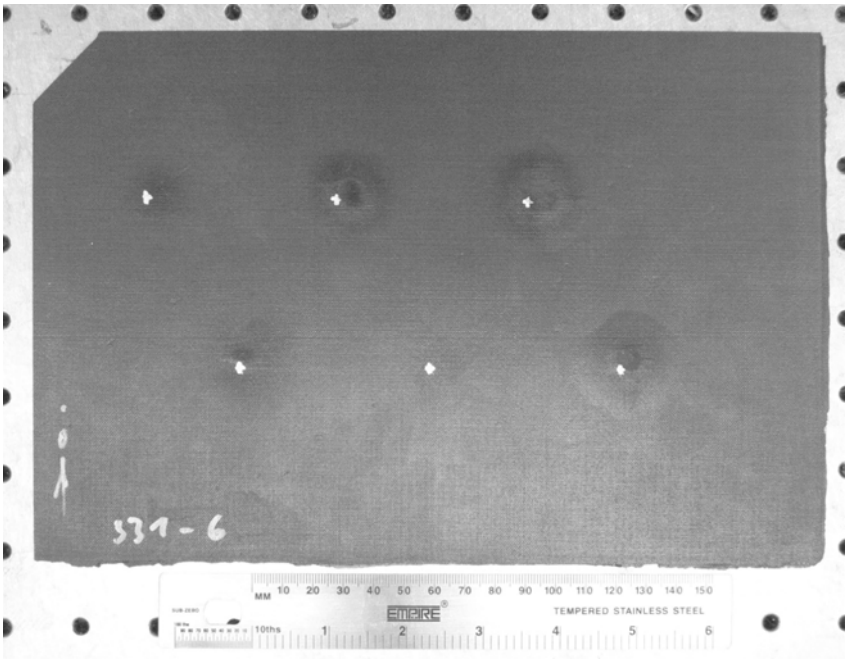
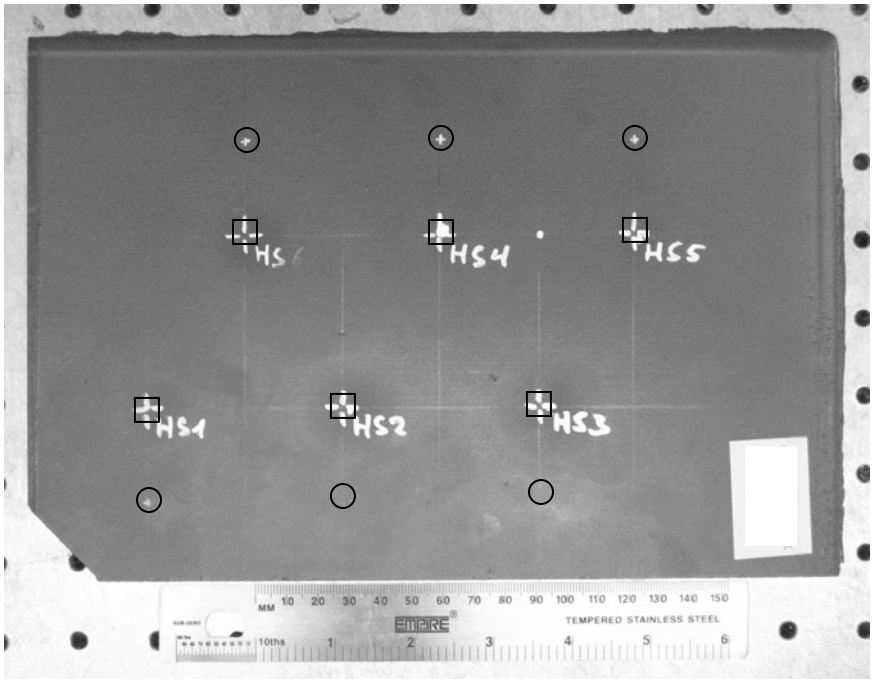
CAPTIONS

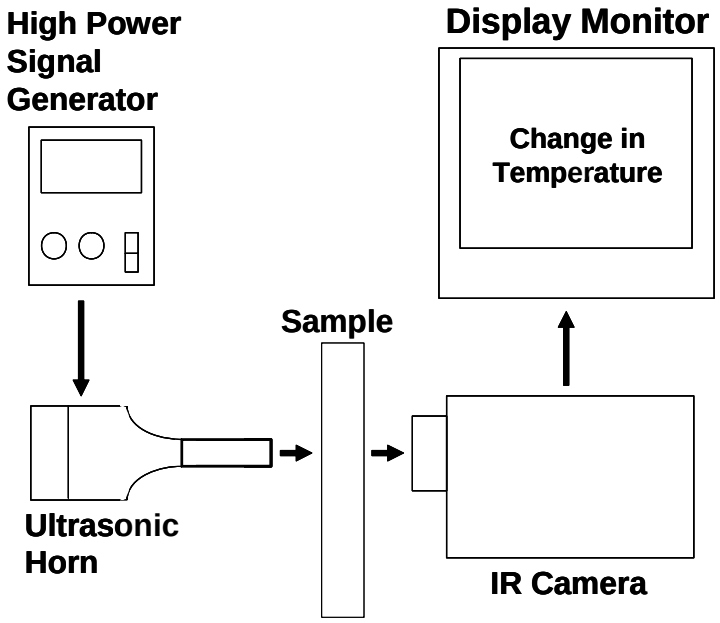
1) Table 1: Heat exposure data
2) Figure 1: Optical image of exposed, unpainted side; white marks indicate center of exposure
3) Figure 2: Optical image of unexposed, painted side; Black squares indicate locations of TC1 and black circles indicate locations of TC2 for damage locations HS1 through HS6
4) Figure 3: Diagram of temperature measurement process
5) Figure 4: C-scan image exposed, unpainted side
6) Figure 5: C-scan image unexposed, painted side
7) Figure 6: Comparison of average rise in temperature vs. average displacement for an undamaged location and damaged locations HS4, HS5 and HS6
8) Table 2: Comparison of x^2 coefficients for an undamaged location and HS4, HS5 and HS6

TABLES AND FIGURES

Location	Exposure Time, s	TC1, °C	TC2, °C
HS1	180	171	97
HS2	360	175	112
HS3	540	185	106
HS4	180	175	89
HS5	360	175	98
HS6	540	190	103




HS1
HS2
HS3
HS4
HS5
TEMPERED STAINLESS STEEL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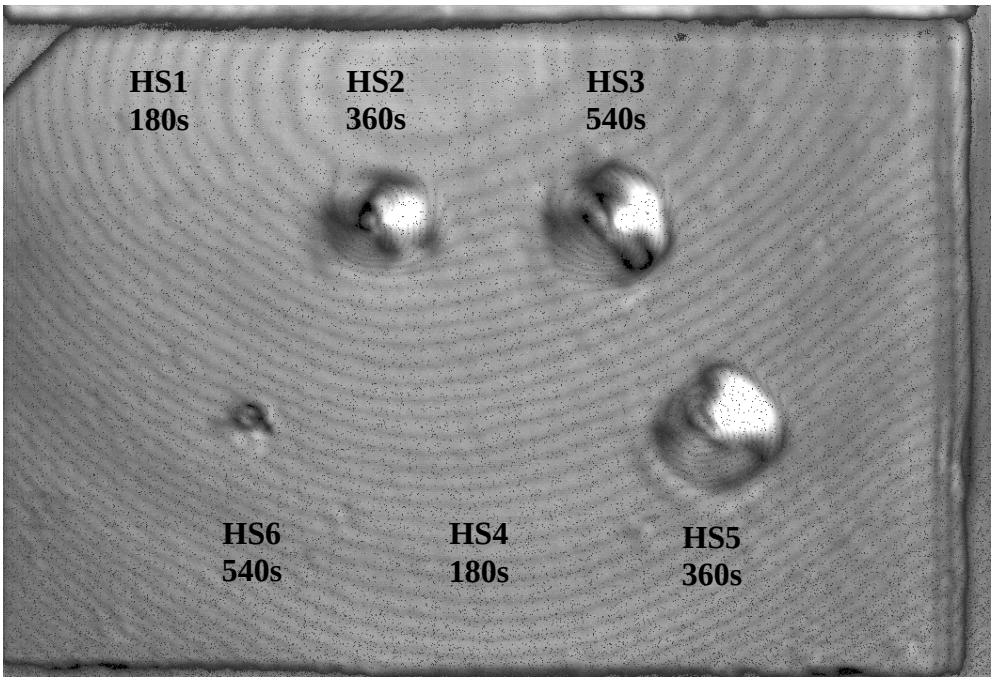
Display Monitor
Change in Temperature
Sample
Ultrasonic Horn
IR Camera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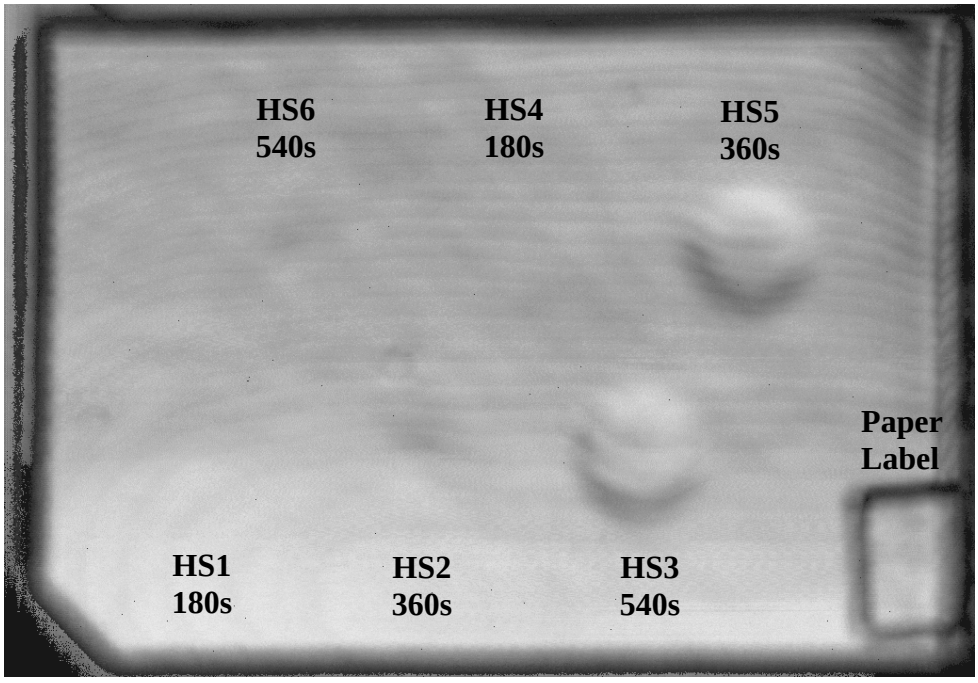
HS2
360s
HS3
540s
HS6
540s
HS4
180s
HS5
360s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HS4
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HS5
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HS2
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HS3
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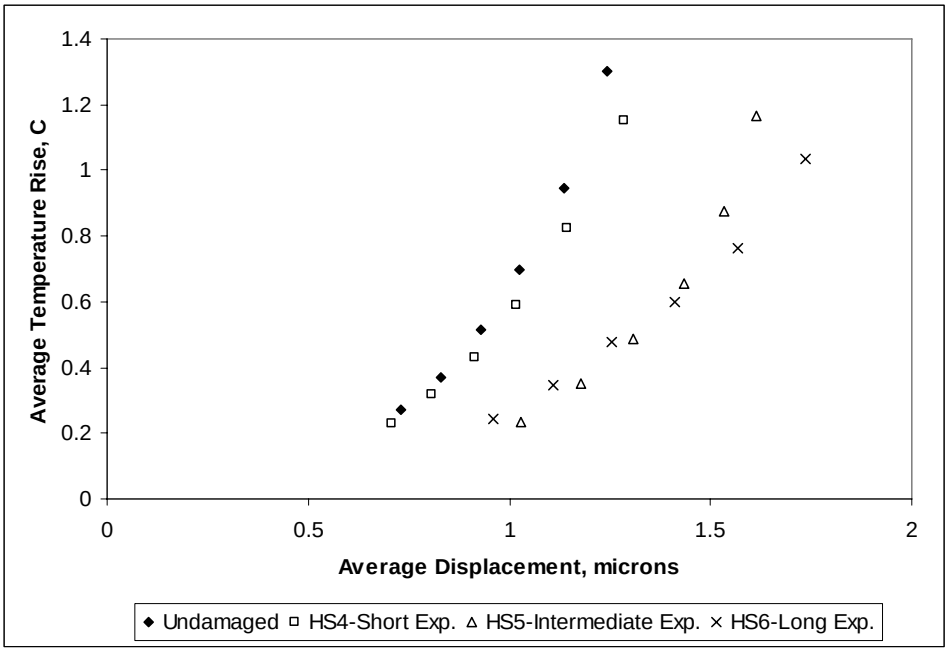

Location #	x^2 Coefficient	Difference from Undamaged	% Difference
Undamaged	1.4		
HS4	1.0	0.4	29
HS5	0.8	0.6	43
HS6	0.4	1.0	71